

FERMILAB-Proposal-850

May 3, 1991

TO: Taiji Yamanouchi
FROM: Bob Kephart *Bob*
SUBJECT: Use of MT test beam to test Diamond detectors

Attached is a proposal given to me by Melissa Franklin that proposes to test Diamond Radiation detectors for the SSC in MT during the upcoming fixed target run. I asked Dan Crane and others to comment on the impact on CDF of doing such a test in MT and all responses I have received so far have indicated that the impact on the CDF program is negligible. (Dan's comments are attached)

At Melissa's request I am forwarding the proposal to you along with the statement that CDF has no objections if the test is approved to proceed as proposed.

May 2, 1991

Taiji Yamanouchi
Fermilab
Fermilab Program Planning
Batavia, IL 60150

Dear Taiji,

The proposal to test Diamond Radiation Detectors in the MTest Beam Line will not interfere with the CDF Test Beam program. The Diamond tests will run in a parasitic mode to CDF data taking. The access requested by the Diamond test group can be scheduled when E795 is running and, therefore, has no impact on the CDF program.

The SVX test table is well suited to the tests that the Diamond group plans to make. There is sufficient rack space for an independent data acquisition system. Discussion between the Diamond group and the CDF test beam about the possibility of adding the Diamond data to the CDF data stream is occurring.

The CDF test beam will experience no detriment from the proposed tests of Diamond Radiation Detectors. The CDF area in MTest is an ideal place for these tests to occur.

Sincerely,



Daniel A. Crane

May 1991

Proposal for Fermilab Test Beam Time of Diamond Radiation Detectors

Abstract

We propose a series of experiments at the Fermilab MTEST test beam to support the development of diamond radiation detectors for use in high energy particle physics experiments. Diamond detectors are envisaged to be uniquely advantaged over all present operational technologies in their ability to withstand high radiation environments, superior speed of charge collection, precise inherent spatial resolution, and potential low cost. At present, a small number of diamond samples have been tested in the low energy (5 GeV) electron test beam at KEK. Both minimum ionizing particles and electromagnetic showers have been observed in diamond radiation detectors. We propose to extend these experiments at Fermilab by testing additional diamond samples in the CDF test beam. Samples will be provided by four manufacturers under a variety of production conditions. The Fermilab test will be used to characterize each sample, to measure the active collection region, and to study flux dependent effects in diamond detectors. The diamond samples will be placed in the location where the CDF silicon vertex detectors were tested in the MTEST beamline and will present less than 3.2% of a radiation length to the calorimeters downstream. The proposed tests should not affect the ongoing CDF program and will be performed as a parasitic experiment.

7/4/95 11:55:58

Proposal for Fermilab Test Beam Time of Diamond Radiation Detectors

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1 Introduction

High energy, high luminosity collider facilities of the future provide a unique opportunity for investigating an unexplored energy region[1, 2, 3, 4]. Experiments at these facilities must have the capability to perform definitive searches for a host of new particles, as well as the ability to recognize unanticipated phenomena. Since the scale of new phenomena is unknown, full exploitation of the physics potential will require operation at the highest possible luminosity.

A detector that can function at high luminosity will have to operate in a severe radiation environment and must be able to handle extremely large event rates. No existing detector technology completely fulfills these requirements. Radiation detectors based on diamond technology are envisaged to have advantages over all existing technologies in their inherent radiation hardness and superior charge collection speed. This technology may make it feasible to construct a detector, at a fraction of the cost of other technologies, with uncompromised tracking and calorimetry which is also capable of operating in the radiation environment of a high luminosity collider. Our recent studies, for instance, establish the possibility that key components of an SSC detector can be based on diamond technology[5].

Although natural diamond has been considered for use in radiation detectors for over 40 years[6], several shortcomings, primarily high cost and impurities, have prevented its widespread adoption. Within the past ten years, however, a new method of manufacturing diamond by Chemical Vapor Deposition (CVD)[7] has been developed for commercial production of diamond. Recent advances show promise of yielding high quality diamond on an economically feasible scale for large area radiation detectors without the inherent problems associated with natural diamond. We propose to conduct a series of experiments at Fermilab to explore the novel use of diamond technology in radiation detectors and determine whether this technology can be applied to high energy particle detectors.

1.1 Characteristics of Diamond

In Fig. 1, we show the basic principle of the use of diamond as a radiation detector. A few hundred volts are applied across a layer of diamond a few hundred microns thick. When a charged particle traverses the diamond, atoms at the crystal lattice sites are ionized, promoting electrons into the conduction band and leaving holes in the valence band. These charges are free to move about the crystal and drift across the layer in response to the applied electric field producing a signal pulse which can be amplified and processed.

In Table 1 we summarize the relevant properties of diamond. Since diamond has a large band gap, 5.5 eV, it is a very good electrical insulator. The conductivity of diamond material is, in fact, dominated by the presence of defects and impurities. The resistivity of high-purity natural diamond is typically 10^{11} Ω -cm to 10^{16} Ω -cm. Because of this large resistivity, a large electric field ($> 10^4$ V/cm) can be applied across the diamond detector without producing significant leakage current. In contrast, the smaller band gap of silicon (and thus lower resistivity) requires the use of a reversed biased *pn*-junction to prevent a large leakage current whose fluctuations would dominate the signal.

Table 1: Properties of Diamond

Property	Diamond	Silicon
Band Gap	5.5 eV	1.1 eV
Resistivity	$> 10^{11}$ Ω -cm	10^5 Ω -cm
Breakdown Voltage	10^7 V/cm	10^3 V/cm
Electron Mobility	1800 $\text{cm}^2/\text{V/s}$	1500 $\text{cm}^2/\text{V/s}$
Hole Mobility	1200 $\text{cm}^2/\text{V/s}$	500 $\text{cm}^2/\text{V/s}$
Saturation Velocity	220 $\mu\text{m/ns}$	100 $\mu\text{m/ns}$
Dielectric Constant	5.6	11.7
Neutron Transmutation Cross Section	3.2 mb	80 mb
Energy to create e-h pair	13 eV	3.6 eV
Mass Density	3.5 gm/cm^3	2.3 gm/cm^3
Ave Min I Signal/100 microns	4,800 e	10,700 e

1.1.1 Charge Collection Speed

As shown in Table 1, the breakdown electric field for diamond is about 10^7 V/cm. It is, therefore, possible to apply a field of a few times 10^4 V/cm to reach the saturation velocity of 2.2×10^7 cm/s, shown in Fig. 2. In silicon, with smaller resistivity, a *pn*-junction is necessary to achieve the required electric fields for operation. However, because of the *pn*-junction and associated depletion region, the maximum field that can be applied before avalanche breakdown is only about 10^3 V/cm. As shown in Fig. 2, this limits the electron velocity to a few times 10^6 cm/s. Since for either diamond or silicon the required detector thickness is a few hundred microns, the collection time would be about 1 ns in diamond compared to about 20 ns and 60 ns for the electrons and holes, respectively, in silicon.

1.1.2 Radiation Hardness

There are two primary manifestations of radiation damage in solid state detectors. One is an increase in leakage current and the other is a decrease in pulse height. Several studies[8, 9] have shown that diamond detectors are very resistant to both types of damage. For silicon detectors, the most serious effect of radiation damage is the increase in leakage current. The amount of radiation induced leakage current should be negligible for diamond detectors. Schottky diodes made with silicon and with diamond were exposed to 1.5 MeV electrons at doses up to $10^{16}/\text{cm}^2$, corresponding to about 1 gigarad[9]. The diamond diode showed no increase in leakage current while the silicon diode showed an increase of about a factor of 40 (see Fig. 3). Even before the exposure to radiation, the leakage current in the silicon diode was about 2 orders of magnitude larger than that of the diamond diode (in Fig. 3 the leakage currents are normalized at low flux for comparison).

The other effect of radiation damage is a decrease in the observed collected charge. This is due to the production of trapping centers resulting in a decrease in carrier lifetime. If the lifetime is small compared to the collection time, the collection efficiency will be low. Diamond is also more radiation resistant than silicon against this type of damage. For a given exposure of radiation, silicon is more sensitive to neutrons than to other types of radiation, as shown in Fig. 4. There is a study by Kozlov *et al.*[8] which shows that a diamond detector can survive up to a few times 10^{14} neutrons/ cm^2 which is about two orders of magnitude greater than silicon (see Fig. 5).

1.1.3 Natural Diamond as a Radiation Detector

The use of diamond as a radiation detector is not new. Hofstader described diamond detectors in a 1949 issue of *Nucleonics*[10]. In fact, the first solid state detector was diamond, presumably because sizable crystals of diamond were more readily available than crystals of silicon or germanium. Despite its early development, diamond did not find widespread use as a radiation detector due to several disadvantages associated with natural diamond. First, natural diamond is prohibitively expensive in large quantities. Second, the inevitable presence of impurities and crystal defects cause some amount of ionized charge to be trapped. Third, because natural diamond contains a large amount of impurities, particularly nitrogen, the carrier lifetime (τ) is short and the collection region ($d = v\tau$) is small. Fortunately, a new technology of manufacturing diamonds by chemical vapor deposition (CVD) has recently been discovered[7, 11] which not only has the potential of solving these technical problems but also allows diamond to be grown at a reasonable cost in large sheets.

1.2 CVD Diamond as a Radiation Detector

In the CVD process, a hydrocarbon gas, such as methane, is mixed with a large concentration of molecular hydrogen gas. The gas mixture is then excited by either microwaves, a hot filament, or some other energy source. The resulting reactive gas mixture is brought into contact with a substrate, typically silicon, where the carbon based radicals are reduced and link together with single bonds (sp^3 hybridized orbitals) forming a diamond crystal.

The CVD growth of diamond can be achieved through several processes and many companies and universities in both the US and Japan are producing polycrystalline CVD diamond. Because of the large number of variables, systematic correlations between growth parameters and diamond quality is only now being developed. One of the main tasks of our collaboration has been to determine which choices of the growth parameters lead to the highest detector quality diamond.

Despite the lack of a complete understanding of the growth process, the following general observations can be made:

- Diamond with thicknesses of up to one millimeter have been grown.
- Growth rates of several hundred microns per hour have been achieved.
- Diamond grown on non-diamond substrates are polycrystalline.
- The crystals tend to grow in columns in the direction of the layer growth. As the layer grows thicker, these columns become longer, extending from one side of the layer to the other. Columns up to 200 microns long have been obtained.
- The lateral crystal size is of the order of 10-50 microns.
- The defect density of the CVD diamond crystals is variable.

Most importantly, the CVD process shows promise of solving the major problems limiting the use of natural diamond: the high cost, small size, and the large trapping center density which leads to a short carrier lifetime and charge buildup. Recently, for example, a diamond manufacturer has quoted a price for large scale CVD diamond production of \$1/cm² x 200 μ . This price is significantly less than the cost of natural diamond or processed silicon. Further, CVD production can be scaled efficiently to cover large areas; standard methods now routinely produce 6 inch diameter diamond wafers. This represents a significant improvement over the traditional high-pressure, high-temperature diamond synthesis methods which produce crystals typically 1 mm in size.

2 Test Beam Program

2.1 Overview

We propose to develop diamond technology for high rate, high luminosity collider experiments. Our research effort in diamond detectors will consist of parallel efforts in (1) developing prototype charged particle tracking devices and calorimeters, and (2) undertaking the necessary materials studies leading to production of high-grade detector material. An essential part of both the tracker and calorimeter prototype programs is the availability of a multi-GeV electron test beam. This is particularly important in the early stage of the program for characterizing individual CVD diamond samples and testing the early prototype detectors. The test beams available at the KEK accumulator ring and FNAL cover the spectrum of incident beam energies and particle species of interest.

Our initial effort in the development of a prototype detector will employ the use of state-of-the-art CVD diamond films. Materials fabricators (e.g., Crystallume, General Electric, Norton, and Sumitomo) will provide diamond samples. The electrical, structural, and mechanical properties of these test samples will be characterized at Lawrence Livermore National Laboratory, Stanford, UC Berkeley and OSU. Transient photoconductivity measurements will be used to measure the carrier mobility (μ) and lifetime (τ). These parameters determine the active region of the diamond over which charge is collected ($d = \mu E \tau$). Charge collection distances will be directly measured in the test beam for each sample and compared with the photoconductivity results.

Of particular importance at this stage of the program will be the detection of ionizing radiation at the Fermilab test beam facilities. These studies allow us to measure the properties of diamond under realistic conditions, give feedback to the materials fabricators, and compare diamond detector performance with other available technologies. All of this information will be used to assist in improving the quality of the diamond and in motivating future detector development.

2.2 Previous Test Results

Recently, members of our collaboration have measured the electrical characteristics of diamond using time resolved photoconductivity[12, 13]. The excitation sources for these measurements are 1) short pulse laser radiation at LLNL (2 ps pulses at 2000 Å) and 2) synchrotron X-rays from the SPEAR storage ring at SSRL (350 ps pulses at approximately

10 Å). The diamond samples are uniformly illuminated with the pulsed radiation. Carrier lifetimes were determined by measuring the decay time of the signal; carrier mobilities were determined by measuring the amplitude of the signal which is proportional to the product of the mobility and the carrier lifetime.

These measurements require repetitive short pulses of photons with an energy greater than the band gap of the material ($E_g=5.5$ eV or 2100 Å). Above band gap radiation is required to intrinsically excite the material (directly excite valence to conduction band transitions). The laser and synchrotron light sources meet these criteria. The time resolution achieved by this technique was less than 100 ps. From these measurements, the carrier mobility and lifetime in the material were inferred, as well as the current-voltage characteristics of the device structures used in the tests. Using this method, the electrical characteristics of natural type IIa diamonds, synthetic high-temperature/high-pressure diamonds, and CVD diamond films grown on silicon were measured. Table 2 summarizes our results to date. The CVD diamonds were grown by two techniques: DC plasma (DC PECVD) and microwave plasma enhanced CVD (μ W PECVD).

Table 2: Properties of diamond samples measured by transient photoconductivity.

Material	Thickness (μ m)	Lifetime (ns)	Mobility ($\text{cm}^2/\text{V/s}$)
Type IIa	1000	0.1-0.4	500-2000
High T/High P	1000	> 10.0	1000
DC PECVD on Si	1-5	0.1-0.3	0.1-1
μ W PECVD on Si	1-10	0.1-0.4	100

There are two important points to be made from this data. One, the required characteristics for a high energy physics detector are nearly equaled by the characteristics measured (preliminary) for the high temperature/high pressure sample (collection distances $d>1\text{mm}$). This implies that there is no fundamental reason why CVD diamond cannot achieve the required characteristics. Two, the difference between the electrical properties of the DC and microwave CVD films is dramatic and is correlated with the quality or diamond character (sp^3 bonding) in the films. The better the quality, the better the electrical properties. The electrical characteristics of the microwave CVD films are approaching those of interest for the present application.

In conjunction with the photoconductivity tests described above our collaboration, during the past five months, has successfully tested natural single crystal and polycrystalline CVD

diamond as radiation detectors in the Accumulator Ring (AR) test beam at KEK in Japan. The AR is an 8 GeV storage ring which is a part of the injection system of TRISTAN. By use of a thin internal target, scattered electrons with energies from 0.5 GeV to 5.5 GeV at rates of a few Hertz can be obtained. Rates of several thousand Hertz can be obtained if a thicker target is used but this considerably reduces the lifetime of the stored beam and is not routinely done since the facility is shared with synchrotron radiation users.

The samples tested at KEK included natural diamond (D34) and a Sumitomo polycrystalline CVD diamond (series 90-01 to 90-06). The natural diamond samples were 1 mm thick (1x3 mm² area) and contained the natural abundance of nitrogen (10-100 ppm). Standard titanium, platinum, gold electrodes were deposited on each side to form ohmic contacts. The CVD diamond samples were prepared by Sumitomo Electric Industries (Japan). They were grown by microwave plasma enhanced CVD on a silicon substrate to a thickness of about 200 μm and cut to 4x4 mm² area. Under scanning electron microscopy, this sample showed a typical needle-like growth of diamond crystals extending across the layer. The sample was prepared for testing in the following manner. After etching away the silicon substrate, each side of the sample was polished. Polishing removed small crystallites at the silicon interface, smoothed the surface, and eliminated gaps between the needle-like crystals. After performing this procedure, the final sample was $\approx 150 \mu\text{m}$ thick and consisted of needle-like crystals which extended from one surface to the other. Successive layers of titanium, platinum and gold were deposited on each side forming 3x3 mm² ohmic contacts.

The test beam setup at KEK is shown in Fig. 6. Scintillation counters plus a small (3x3 mm²) silicon detector define the incident electron beam and form the trigger. A removable lead stack is available to create electromagnetic showers and thereby increase the numbers of particles transversing the detectors. Signals from a diamond detector and a silicon detector were measured and compared. Figures 7 and 8 show typical minimum ionizing signals as seen by the natural diamond detector (upper trace) and by the silicon detector (lower trace). Figure 9 shows the corresponding signal from a CVD diamond detector (upper trace) and silicon detector (lower trace).

The quantity used to characterize the diamond in these tests is the charge collection distance (d). The collection distance is calculated from the photoconductivity measurements using the mobility (μ), the carrier lifetime (τ), and the applied electric field (E):

$$d = v\tau = \mu E\tau$$

The pulse height or average charge collected (\bar{Q}) in a beam test is related to the collection

distance (d) by:

$$\bar{Q} = \int_0^t \bar{n} dx \int_{t-x}^{\text{inf}} \frac{1}{d} e^{-l/d} dl = \bar{n} \int_0^t e^{-(t-x)/d} dx$$

where t is the material thickness and \bar{n} is the average number of electron hole pairs produced per unit length. Then:

$$\bar{Q} = \bar{n}d(1 - e^{-t/d})$$

or:

$$\bar{Q} \approx \bar{n}d \quad \text{when } d \ll t$$

and

$$\bar{Q} \approx \bar{n}t \quad \text{when } d \gg t.$$

All samples tested to date have fallen into the category where $d \ll t$. The number of electron hole pairs in diamond has been calculated in two ways: (1) by normalizing the diamond pulse height to the silicon pulse height after correction for solid angle and dE/dx , and (2) using the EGS monte carlo. Both methods agree. Table 3 summarizes the results of the KEK test for two samples and compares with the photoconductivity data ($\mu E\tau$).

Table 3: KEK test beam results.

Material	E (V/cm)	Collection Distance (microns)	$\mu E\tau$ (microns)
Type IIa (D34)	1×10^3	9 ± 2	10 ± 2
	3×10^3	16	18
	1×10^4	35	33
CVD (90-06)	1×10^4	2	-
	3×10^4	4	-
	4×10^4	6	-

The data for the diamond detectors were obtained at relatively low applied electric fields (10^4 V/cm) where the carrier velocity was not saturated. In the case of natural diamond where both the test beam and photoconductivity measurements have been performed there is remarkable agreement in the two measurements indicating that the detectors were performing

as expected. Increasing the applied electric field should increase the collection distance dramatically since the device is not saturated. The photoconductivity measurements have not yet been performed on the Sumitomo CVD sample. It also appears that the CVD sample was not saturated and would gain from larger applied field. This experiment was *the first demonstration that CVD diamond can detect charged particle minimum ionizing radiation*. These preliminary results are very encouraging.

2.3 The Fermilab Beam Test

The initial beam studies performed at KEK will be extended at FNAL. The KEK studies of single layers of diamond have demonstrated that natural, synthetic (high T/high P) and CVD diamond can detect both electron showers and minimum ionizing particles. One of the goals of the Fermilab tests is to map the collection distance as a function of electric field strength for each sample. We expect to perform this test on samples from Sumitomo (3 samples), GE (3 samples), Crystallume (3 samples), and Norton (5 samples). Most of these samples are already in hand. A secondary purpose of this study will be to compare the measured pulse height with the result of an EGS calculation and the photoconductivity studies to provide an important check of how well we understand the charge collection process in diamond. In addition to characterizing the diamond, this test-beam study will allow us to begin to develop a readout system (electrodes, readout lines, preamp) in a more realistic environment than provided by bench measurements and also allow us to investigate possible rate dependent effects.

2.4 Test Proposal

The FNAL test beam provides electrons with energies in the range 5-150 GeV. As such, this facility nicely compliments the lower energy KEK test beam. Using both facilities will allow complete testing of prototype detectors under a wide variety of conditions.

The FNAL test beam station is well equipped for tests. There is an adjustable table for precisely setting the horizontal and vertical positions of the test device. A micro-VAX based data acquisition system is in place with software that can easily be modified for specific tests. There are also single wire drift chambers which can be used for monitoring the beam position and a functioning data acquisition system.

The proposed test beam setup at FNAL is shown in Fig. 10. Existing scintillation counters plus wire chambers will be used to determine the impact point of the incident

electron. The diamond sample will be placed in front of the CDF calorimeters where the CDF silicon vertex detector tests were performed. A calibrated silicon detector will be placed immediately in front of the diamond sample. Signals from the diamond detector and a silicon detector will be read out through a charge sensitive preamp and shaping amplifier into a digital oscilloscope and peak sensing ADC. One possibility for data readout is to use the CDF data acquisition system. We will add less than 50 words to the data stream. If this is not possible, we will use our own (Rutgers) Microvax 3200 and use standard CAMAC. This all fits in the rack presently at MTEST which was used for the silicon vertex detector. The total additional material added to the test beam is two 100μ thick silicon detectors and one 200μ diamond detectors plus mounting (3x1/32 inch G-10 pc boards) and shielding (1/16 inch Al). This represents an additional 3.2% of a radiation length.

The samples that we intend to test include new samples manufactured by Crystallume (3), General Electric (3), Norton (5), and Sumitomo (3), the previously tested samples from Sumitomo, and the previously tested natural diamond sample. These samples should span the present production parameters of each manufacturer. A total of 17 samples will be tested. The average pulse height vs applied electric field will be measured for each sample. Typically five different high voltage settings will be used with 500-1000 events accumulated at each setting. In addition, high flux dependent effects (in particular material polarization) will be studied in the natural diamond and a subset of the CVD diamond.

The estimated time required to perform these tests is thirty days. We believe this can be accomplished by running parasitically during the CDF test beam run. In addition, we will require two days of access for setup and one day of access for breakdown.

References

- [1] E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, "Supercollider Physics", *Rev. Mod. Phys.* **56**, 579 (1984).
- [2] Proceedings of the DPF Summer Study on the Physics of the Superconducting Super Collider, Snowmass 86, FNAL (1987).
- [3] Proceedings of the Workshop on Experiments, Detectors and Experimental Areas for the Supercollider, Berkeley 87, World Scientific (1988).
- [4] Proceedings of the DPF Summer Study on High Energy Physics in the 1990's, Snowmass 88, World Scientific (1989).
- [5] R. Plano *et al.*, "A Compact Diamond-Based Detector for the SSC", SSC-EOI0009 (1990).
- [6] D. Wooldridge, A. Ahearn, and J. Burton, "Conductivity Pulses Induced in Diamond by Alpha-Particles", *Phys. Rev.* **71**, 913 (1948).
- [7] J. Angus and C. Hayman, "Low-Pressure, Metastable Growth of Diamond and 'Diamondlike' Phases", *Science* **241**, 913 (1988).
- [8] S.F. Kozlov *et al.*, "Preparation and Characteristics of Natural Diamond Nuclear Radiation Detectors", *IEEE Transactions on Nuclear Science NS-22*, 160 (1975).
- [9] M. Geis, MIT Lincoln Laboratory, private communication.
- [10] R. Hofstader, "Crystal Counters", *Nucleonics* 1949.
- [11] W. Yarbrough and R. Messier, "Current Issues and Problems in the Chemical Vapor Deposition of Diamond", *Science* **247**, 688 (1990).
- [12] L.S. Pan *et al.*, "Intrinsic Photoconductivity in Polycrystalline CVD Diamond Films and in Natural and Synthetic Bulk Diamond", Second International Conference on the New Diamond Science and Technology, Washington D.C. (1990).
- [13] D.R. Kania *et al.*, "Absolute X-ray Power Measurements with Subnanosecond Time Resolution using Type IIA Diamond Photoconductors", *Jour. Appl. Phys.* **68**, 124 (1990).
- [14] E.A. Konorova and S.F. Kozlov, "Nuclear Radiation Detectors Made of Diamond", *Sov. Phys.-Semi.* **4**, 1600 (1971).

Figure Captions

1. Schematic of use of diamond as a radiation detector.
2. Electron drift velocity in various materials as a function of applied electric field.
3. Normalized leakage current for diamond and silicon diodes exposed to a flux of 1.5 MeV electrons. The curves are normalized at 10^{12} e/cm². Figure is courtesy of M. Geis, MIT Lincoln Laboratory.
4. Lifetime degradation in silicon from exposure to neutron, electron, and proton radiation.
5. Comparison of radiation resistance of diamond (solid curves) to silicon (dashed curves) based on measurements with an α -source after exposure to a flux of fast neutrons (maximum in spectrum of 0.5 MeV).
6. Test beam setup used at KEK.
7. Minimum ionizing single pulses in Natural Diamond (upper trace) and Silicon (lower trace). The Diamond to Silicon pulse height ratio on this particular pulse was 1/10.
8. Minimum ionizing single pulses in Natural Diamond (upper trace) and Silicon (lower trace). The Diamond to Silicon pulse height ratio on this particular pulse was 1/2.
9. Minimum ionizing single pulses in CVD Diamond (upper trace) and Silicon (lower trace). The Diamond to Silicon pulse height ratio on this particular pulse was 1/8.
10. Proposed test beam setup at Fermilab.

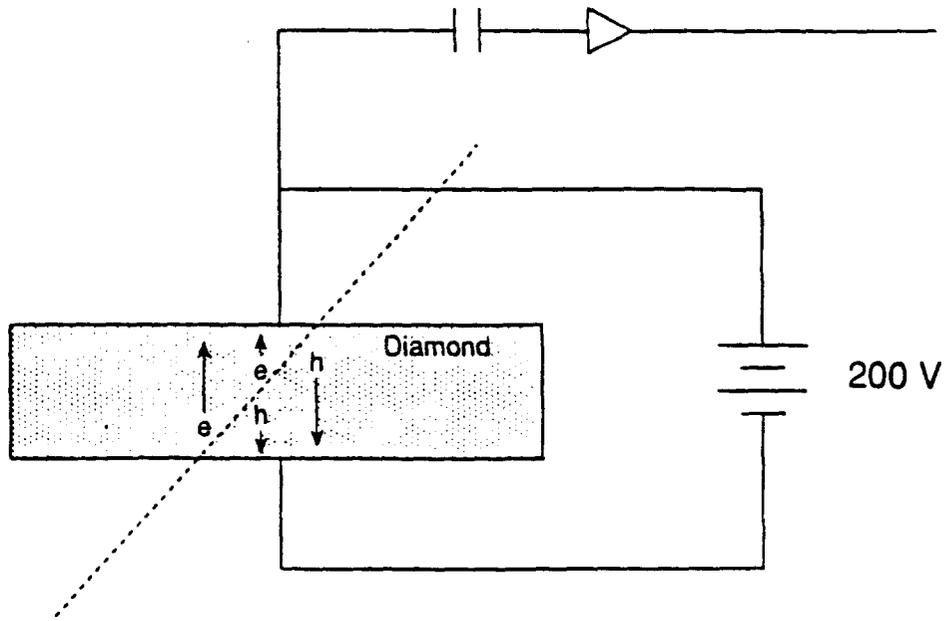


Figure 1

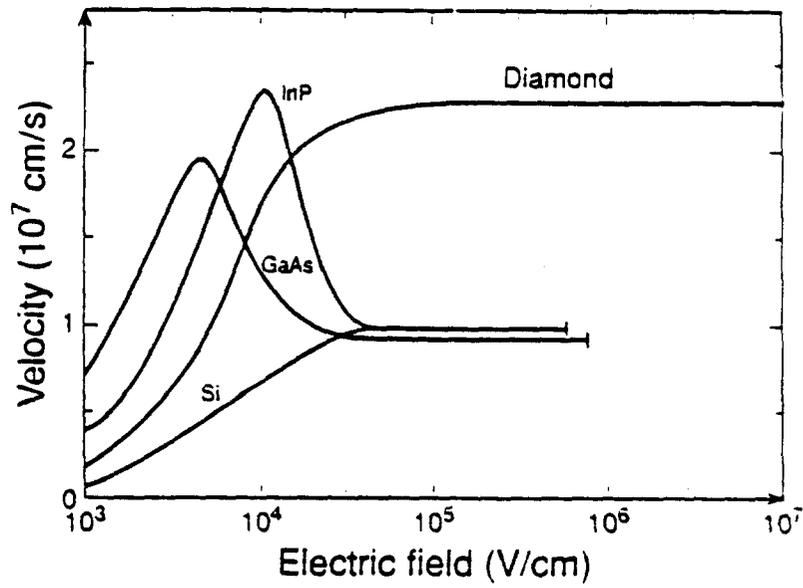


Figure 2

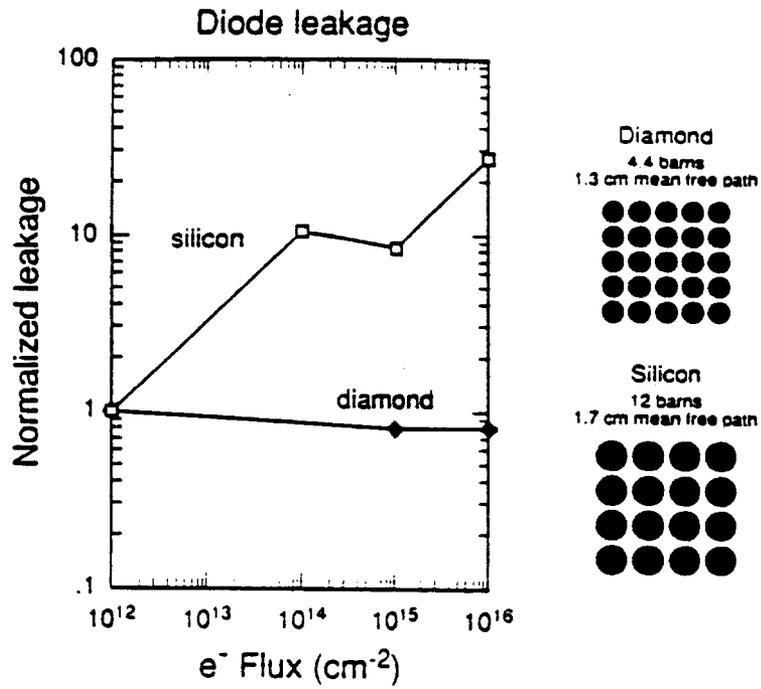


Figure 3

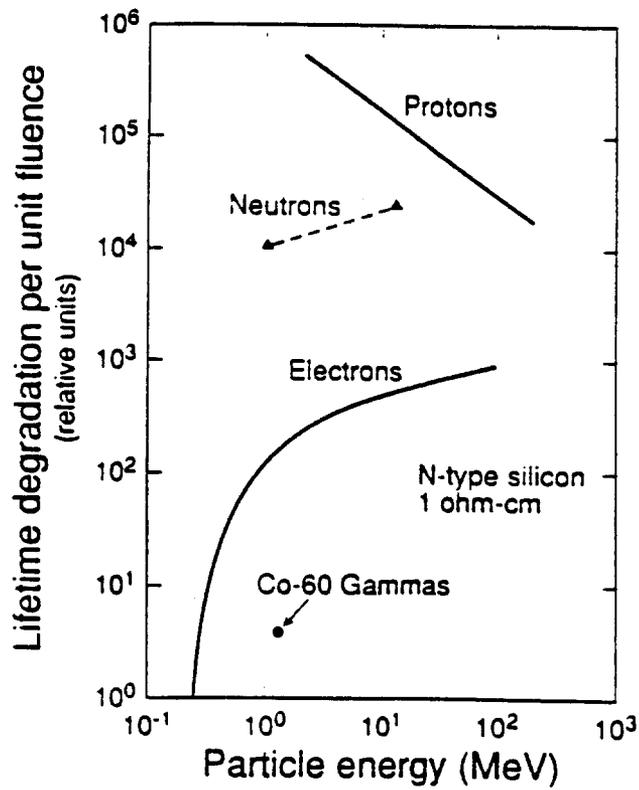


Figure 4

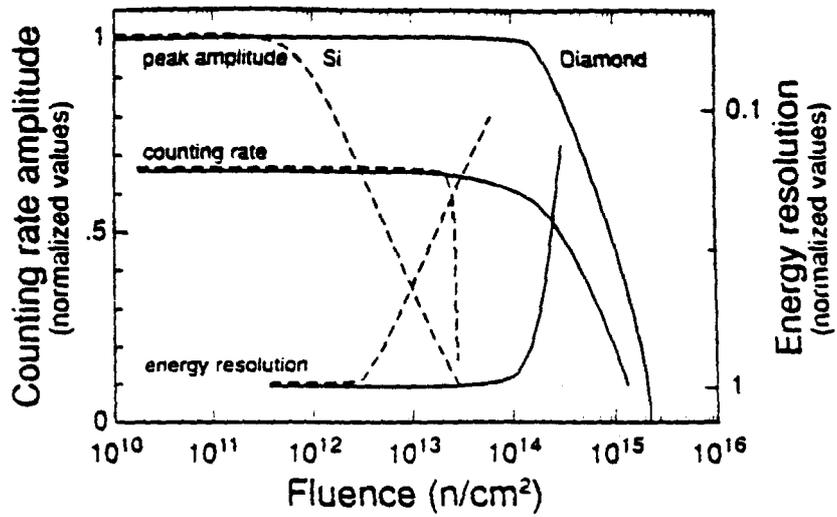


Figure 5

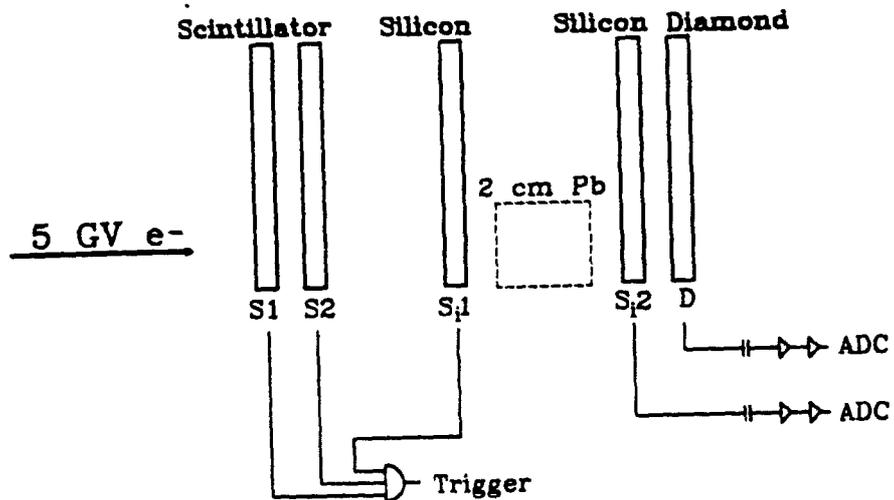


Figure 6 .

CH1 10mV A 5ms -40.6mV EXT1
CH2 200mV

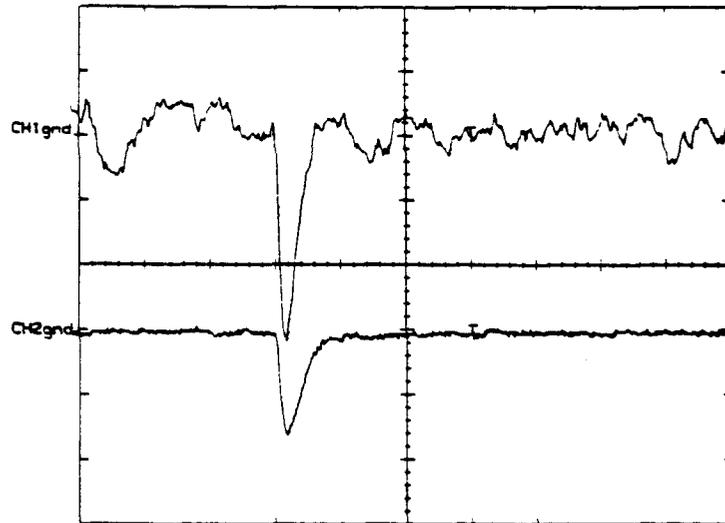


Figure 7

CH1 20mV A 5ms -192mV EXT1
CH2 20mV

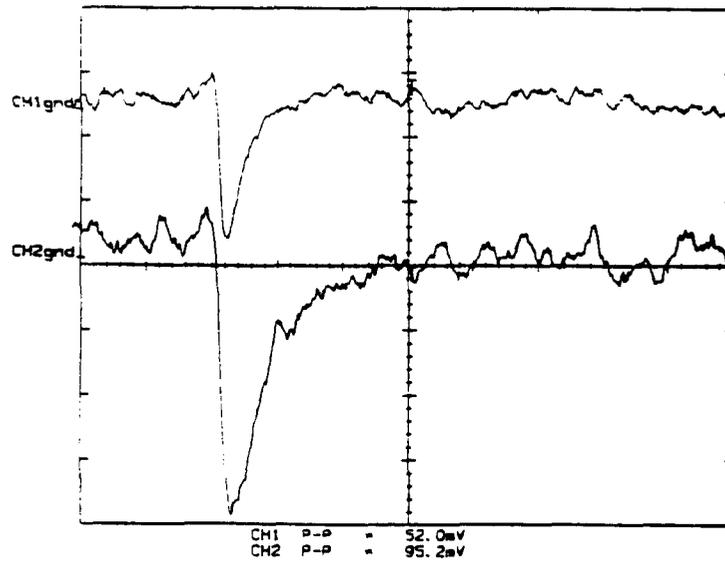


Figure 8

CH1 10mv
 CH2 50mv
 A 5ms -192mv EXT:

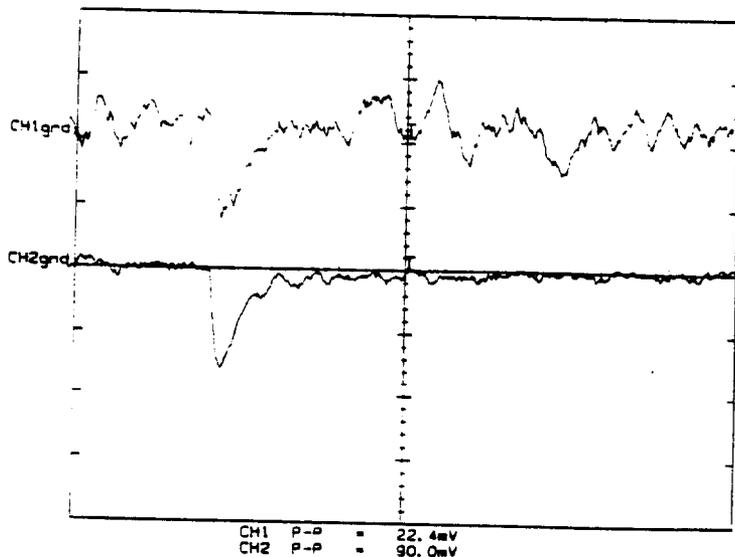
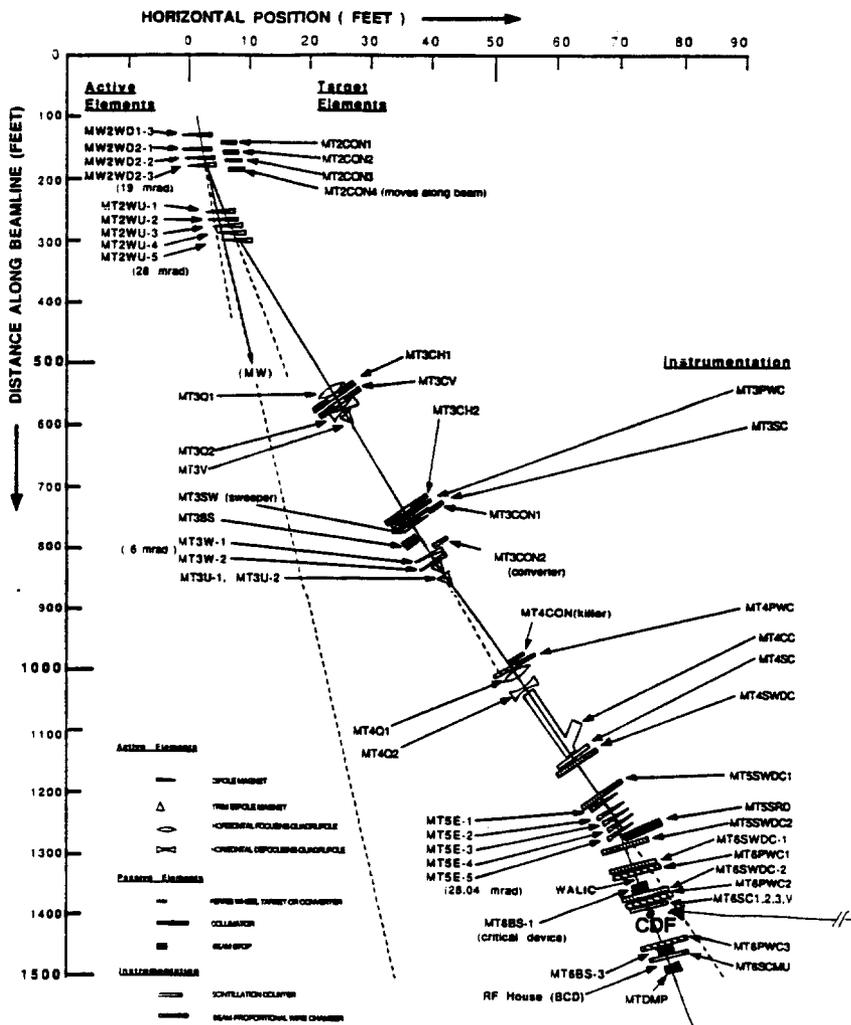


Figure 9



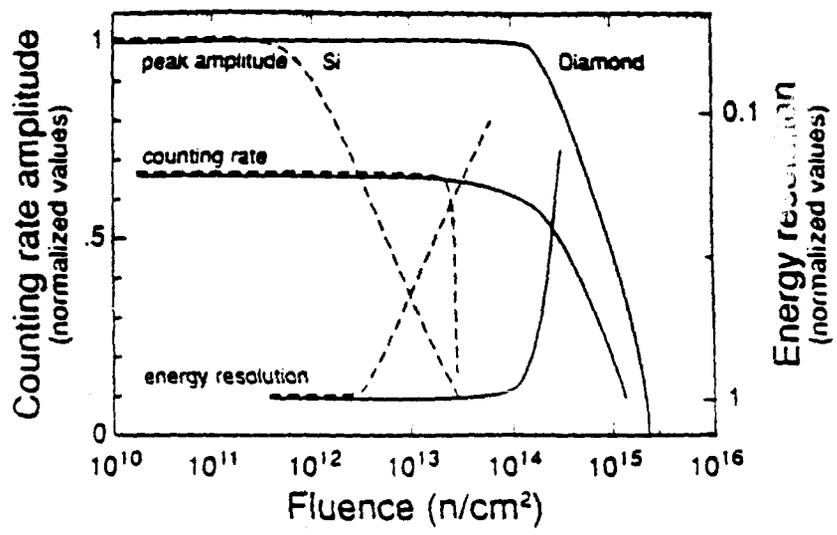


Figure 5

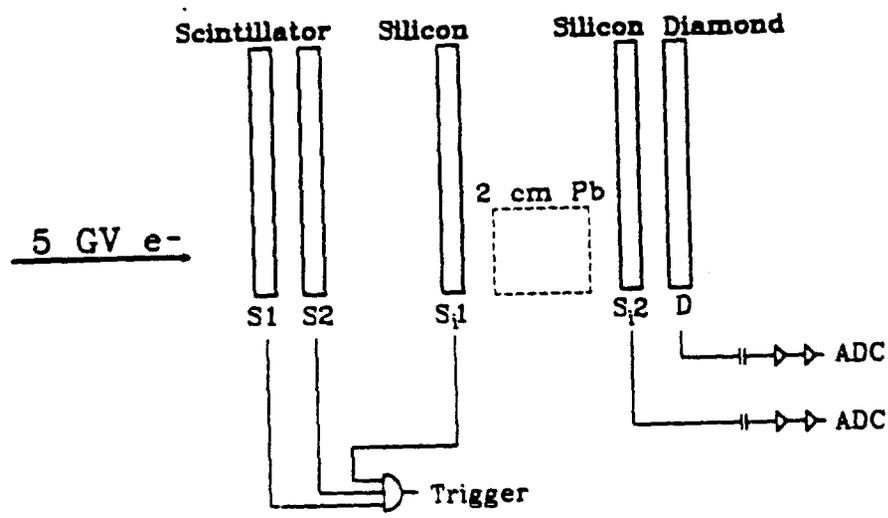


Figure 6